91602
new 82-10

LEGAL NOTICE

This report was prepared by Ontario Hydro and, while effort has been made to assure the accuracy and applicability of the material contained herein, neither Ontario Hydro nor any person acting on its behalf:

(a) makes any warranty, express or implied with respect to the use of any information, apparatus, method or process disclosed in this report or that such use may not infringe privately owned rights; or

(b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

ontario hydro
research division

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if Reproduced in Whole or in Part

NONDESTRUCTIVE AND FRACTURE EVALUATION SECTION 1987 REVIEW AND 1988 WORK PROGRAM

Report No. 88-38-K

J.A. Baron
Section Head

ABSTRACT

The projects and achievements of the Nondestructive and Fracture Evaluation Section in 1987 are reviewed. Proposed projects and objectives for 1988 are described in outline.

JAB
JS

job	file	date	report no.
	826.0	April 7, 1988	88-38-K

TABLE OF CONTENTS

		Page
I	INTRODUCTION	1
II	1987 WORK PROGRAM REVIEW	3
	1.0 NONDESTRUCTIVE EVALUATION	3
	1.1 NDE Techniques R&D and Applications	3
	1.2 Inspection Systems Development	5
	1.3 Pressure Tubes	10
	2.0 FRACTURE MECHANICS RESEARCH AND APPLICATION	15
	2.1 Darlington Leak-Before-Break Program	15
	2.2 Pressure Tubes	17
	2.3 Plant Materials	19
	2.4 Analytical Fracture Mechanics	21
	2.5 External Activities	21
III	SUPPORT TO THE EXTERNAL COMMUNITY	23
IV	THE VALUE OF FORWARD LOOKING RESEARCH	25
V	SUMMARY	25
DISTRIBUTION		last page

CROSS INDEX BY CLIENT OR INTEREST GROUP

	Page
BRUCE NGS	
Detecting Failure of Fibre Reinforced Rubber Using Acoustic Emission	3
PIPE – Packaged Inspection Probe (Bruce Version)	5
Data Acquisition System	6
Bruce PIPE – Commissioning	6
DARLINGTON GS	
Detection Failure of Fibre Reinforced Rubber Using Acoustic Emission	3
Darlington NGS Scanning Tool for Elongation Measurement (STEM)	10
Darlington 4 Pressure Tube Manufacturing Inspection	11
Darlington Leak-Before-Break Program	15
Application of Elastic-Plastic Fracture Mechanics	15
Fatigue Crack Growth Modelling	15
Darlington Leak-Before-Break Material Test Program J-Resistance Curves	15
Fracture Toughness of PN-229 Submerged Arc Weld Metal	20
Finite Element Mesh Generator	21
PICKERING NGS	
Detecting Failure of Fibre Reinforced Rubber Using Acoustic Emission	3
Synthetic Aperture Focusing for Pickering Manway Inspection	3
Pickering 3 Boiler 5 Rolled Joint Assessment	5
BLIP – Blister and Spacer Location Inspection Probe	7
Full Size Mechanical Simulation and Test Facility	8
PIPE – Packaged Inspection Probe (Pickering Version)	7
Fracture Properties of Pickering 'A' Primary Head Weldment	19
DESIGN AND DEVELOPMENT – GENERATION	
Demonstration of Robotic Inspection of Final Closure Weld of High Level Nuclear Used Fuel Container	4
Irradiated Fuel Verificiation Device	4
PIPE – Packaged Inspection Probe (Bruce Version)	5
Data Acquisition System	6
Bruce PIPE – Commissioning	6
BLIP – Blister and Spacer Location Inspection Probe	7
Full Size Mechanical Simulation and Test Facility	8
CIGAR	8
Overview	8
Gauging	8
Sag	8

	Page
Gap	8
Flaw Detection	8
CIGAR Gap Measurement	9
CIGAR Head Tester	9
CIGAR - Profilometry Inspection Head	9
CIGAR - Visual Inspection System	9
Up and Coming	10
Pressure Tube Sag Measurement	10
Application of Elastic-Plastic Fracture Mechanics	15
Fatigue Crack Growth Modelling	15
Darlington Leak-Before-Break Material Test Program J-Resistance Curves	15
Allowable Sizes of Blunt Flaws in Zr-Nb Pressure Tubes Under SLAR Loads	17
Fracture Toughness of Pn-229 Submerged Arc Weld Metal	20
NEW BUSINESS VENTURES	
CIRENE-CIGAR	10
TECHNICAL AND TRAINING SERVICES	
Synthetic Aperture Focusing for Pickering Manway Inspection	3
Pickering 3 Boiler 5 Rolled Joint Assessment	5
PIPE - Packaged Inspection Probe (Bruce Version)	5
Data Acquisition System	6
Bruce PIPE - Commissioning	6
PIPE - Packaged Inspection Probe (Pickering Version)	7
BLIP - Blister and Spacer Location Inspection Probe	7
Full Size Mechanical Simulation and Test Facility	8
CIGAR	8
Overview	8
Gauging	8
Sag	8
Gap	8
Flaw Detection	8
CIGAR Gap Measurement	9
CIGAR Head Tester	9
CIGAR - Profilometry Inspection Head	9
CIGAR - Visual Inspection System	9
Up and Coming	10
Pressure Tube Sag Measurement	10
Darlington 4 Pressure Tube Manufacturing Inspection	11
Pressure Tube Offcut Inspection	11
Crack Depth Measurements in Pressure Tubes	12
On-Power EMAT Transducer	13
Inspection of a Darlington 4 Pressure Tube	14
Inspection of Yttrium D_2 Sinks for Pressure Tubes	14
Zirconium Hydride Blister Cracking Tests	18
Effects of Hydride Morphology on Zr-2.5Nb Fracture Toughness	18

	Page
Thermal Plant Flaw Evaluations	19
Fracture Properties of Pickering 'A' Primary Head Weldment	19
Fracture Toughness of A-515 Gr 70 Pressure Vessel Steel	19
Fracture Properties of Downcomer Weld of Lakeview TGS, Unit 5	20
COG	
Crevice Corrosion Defect Sizing	4
Hydrogen Concentration Measurement	11
Crack Depth Measurements in Pressure Tubes	12
Hydride Platelet Concentration Measurements	12
Pressure Tube Leak Detection Using Acoustic Emission	13
Empirical PoD Model for Blisters	13
Comparison of CIGAR and New Manufacturing Inspections	13
SLAR - Blister Detection System	13
Allowable Sizes of Blunt Flaws in Zr-Nb Pressure Tubes Under SLAR Loads	17
Fatigue Crack Growth of Zr-Nb Pressure Tube Material	17
Commissioning of a Pressure Tube Burst Test Facility	17
Zirconium Hydride Blister Cracking Tests	18
BHWP	
Bruce Heavy Water Plant (BHWP) Ultrasonic inspections	4
LAKEVIEW GS	
Thermal Plant Flaw Evaluations	19
Fracture Properties of Downcomer Weld of Lakeview TGS, Unit 5	20

91601
new 82-10

ontario hydro
research division

To Dr. D. Mills
Director of Research

NONDESTRUCTIVE AND FRACTURE EVALUATION SECTION
1987 REVIEW AND 1988 WORK PROGRAM

I - INTRODUCTION

As in previous years, the Section had difficulty in fulfilling its OM&A work program due to heavy client demands in both nondestructive evaluation and fracture mechanics. However, the Candu Owners Group has supported a number of high priority forward looking projects plus good use has been made of the OM&A funding in terms of advancing the technologies represented within the Section.

Not surprisingly, a very high proportion of the Section's endeavours were directed at fuel channels and, in total, only two small projects were undertaken outside of the Nuclear Generation program area.

A description of the 1987 work program follows and our intentions for 1988 are highlighted.

Section Personnel

Nondestructive Evaluation

Senior Research Engineer	Dr. M.P. Dolbey

Nondestructive Evaluation Unit

Engineers	Dr. M.D.C. Moles Mr. W.K. Chan Mr. E. de Buda Mr. D.W. Donnelly Mr. J.H. Sedo Ms. M.A. Kowakchuk Mr. S.M. Kramer
Technologists	Mr. A.L. Allen Mr. E. Bernacchia Mr. B. Antonacci
Technicians	Mr. J.R. Boon Mr. G.E. Truemner Ms. F.C. Earl Mr. K.C. Watt*

Attached Staff (University of Toronto)	Mr. K.-E. Lindenschmidt

*Joined the Section in September.

The objectives and principal research interests of the Unit are:

- Design and development of remotely operated, electromechanical scanning systems for nondestructive examination of nuclear station components to reduce man-rem expenditure and improve inspection reliability.
- Evaluation of new concepts and development of equipment to enable remote and precise spatial measurements in nuclear power stations.
- Research into limitations of, and applicability of, nondestructive testing techniques for defect detection and evaluation, particularly with regard to nuclear periodic inspection requirements.
- Development of new nondestructive techniques and procedures for particular applications at generating plants and transmission systems.
- Investigation of signal analysis methods for improved defect characterization.
- Assistance to operational groups with non-routine inspection problems, major system breakdowns, and service inspection requirements.

Fracture Mechanics

Unit Head – Fracture Mechanics	Dr. B. Mukherjee
Engineers	Mr. M.L. Vanderglas Mr. D.A. Scarth Mr. A.C. Wallace Mr. O.E. Lepik
Technologists	Mr. D.W. Carpenter Mr. D.M. McCluskey
Technician	Mr. J. Schaefer*

*Joined the Section in May.

The objectives of the Unit are:

- Assess the impact of flaws and off-design operation of the reliability and safety of major plant components.
- Propose and evaluate new methodology for flaw-structure interaction analysis that will quantify the real margins of safety of pressure bearing components.

- Improve quantitative understanding of the effects of plant chemistries, materials and fabrication processes and stress state on performance of major plant components.

The main research interests of the Unit are:

- Research into experimental and computational aspects of fracture mechanics.
- Determination of fatigue and fracture properties of generating plant and transmission system materials under operating environmental conditions.
- Investigation of techniques for service life prediction of components.
- Development of new fracture mechanics analysis procedures where conventional techniques are inappropriate.
- Development of rapid structural integrity evaluation methods to meet jurisdictional requirements.

II - 1987 WORK PROGRAM REVIEW

1.0 NONDESTRUCTIVE EVALUATION

1.1 NDE Techniques R&D and Applications

Detecting Failure of Fibre Reinforced Rubber Using Acoustic Emission

Fibre reinforced rubber is used as gasket material in reactor containment ducting. An investigation is underway to determine the effects of material flaws on gasket performance and to develop methods to detect flaws prior to installation and proof testing.

As part of the investigation, material tests have been performed. Results indicate that acoustic emission monitoring can readily detect flaw growth in various types of fibre reinforced rubber. Subsequent tests will use AE monitoring to help determine the behaviour of gasket material during proof tests, and possibly to test material prior to installation.

32 Channel AE System Upgrade

The AET 32 channel acoustic emission (ae) system has been partially upgraded. Software has been developed to display and store data, using a COMPAQ 286 microcomputer. From time difference data obtained from 3 or 4 channels, ae sources can be located and their relative positions displayed on a two-dimensional grid map.

Synthetic Aperture Focusing for Pickering Manway Inspection

Ultrasonic inspection of Pickering manway welds has presented an ongoing problem due to the complex geometry of the component and the difficulty encountered in adequately focusing an ultrasonic beam at a depth of 88 mm. A program was thus begun to investigate the synthetic aperture focusing technique (SAFT) as a method

for computerized focusing of unfocussed data sets. Software has been developed to obtain complete RF waveforms, perform appropriate signal conditioning, and perform SAFT. To ensure portability, the system under development incorporates an ultrasonic pulser/receiver and high speed A/D converter installed in a Compaq personal computer. Laboratory tests of SAFT using test blocks and mockups of the manway indicate potential for the accurate sizing of defects as small as 2 mm.

Demonstration of Robotic Inspection of Final
Closure Weld of High Level Nuclear Used Fuel Container

A second procedure for mapping out closure welds using the PUMA 560 robot has been developed. The first procedure uses a waterjet to both map the surface, and to inspect the weld. The second procedure uses a touch sensor to map the surface, followed by a waterjet ultrasonic inspection of the weld. The touch sensor proved to be much more rapid than the waterjet for mapping, but was not able to measure the normal orientation accurately enough to reliably inspect the titanium diffusion bond. The waterjet technique is limited to vertical surfaces, whereas the touch sensor could map any shape, in principle. Comparison between the robotic inspection and a previous conventional immersion inspection showed that the waterjet technique gave similar results.

Bruce Heavy Water Plant (BHWP) Ultrasonic Inspections

Six blistered plates were shipped to Research to determine whether the BHWP thickness meter testing results correlated with conventional C-scans performed by Research. The comparison showed that the thickness meters detected the few significant defects, and gave accurate wall thickness measurements. Later, a domed head was sent to Research for blister mapping. This head was mapped and scanned with the PUMA 560 robot, using the touch sensor. In general, the robot's scan results were good, with many blisters and their depth ranges mapped. However, the robot's software showed some problems, for example, it was limited in its scan size due to a tendency to curl up at the ends of the scan.

Irradiated Fuel Verification Device

A system is being developed for verifying that spent fuel in the spent fuel bays has not been tampered with. The concept involves a device which moves a radiation sensor across the fuel bundles through the small gap in between the fuel bundles in the storage trays. A prototype for the horizontal access portion of the delivery system for the probe has been built and demonstrated. The sensor is still being developed by the Science Section. Further development is required for the vertical access portion of the delivery system, as well as cabling and position feedback.

Crevice Corrosion Defect Sizing

Crevice corrosion defects are typically wide shallow surface breaking pits. The traditional eddy current technique of utilizing the phase angle of the indication to estimate the defect depth is difficult or impossible to apply as the angles involved are small and similar. An alternative is to look at the magnitude of the liftoff response (essentially the magnitude of the entire response) as a function of position. The curves are suggestive of the cross section of the defect but are widened and smoothed. As a result the average depth and width of the defect cannot be

determined from the curve in a straight forward manner. Previous work suggested that this curve could be considered the result of a convolution of the probe's influence function and the defect's cross section.

This year a project was begun to examine methods of reconstructing the profile of the defect from the smooth probe response. Early in the investigation it was concluded that the use of only a few parameters of the response was too sensitive to noise and modelling assumptions. Attention was then turned to the mathematical field of deconvolution where every point of the response is utilized. The basic concept is fairly straightforward, however, it is greatly complicated by fact that the process is noise enhancing and not necessarily unique. Four of many published algorithms have been selected and implemented thus far; time domain deconvolution, modified Wiener filtering, the conjugate gradient method and the positively constrained conjugate gradient method. All have shown some degree of resolution enhancement but further work is required to formalize the choice of turning parameters and to suppress the growth of oscillations in the results.

Pickering 3 Boiler 5 Rolled Joint Assessment

In 1985 the inlet tubesheet of P3B05 was found to be damaged by debris trapped in the primary head. There is some concern that the hammering by the debris may have separated the rolled joints beyond the protective Monel cladding.

A project was undertaken to evaluate the capability of existing eddy current probes to detect this condition. A dual frequency technique with a standard probe was demonstrated but it required that the probe have clean passage through the tube. Many of the tubes have been hammered partially or completely closed and so a redesign of the probe was recommended. Efforts are underway to place the sensing elements at the front of the probe without sacrificing performance. A test mockup with controlled rolled joint separation will be obtained to evaluate the probe and technique under realistic conditions.

1.2 Inspection Systems Development

PIPE – Packaged Inspection Probe (Bruce Version)

Introduction

The Bruce PIPE concept makes use of a modified fuelling machine to do ultrasonic inspection of CANDU fuel channel rolled joints. The ultrasonic transducers are mounted into a transducer carrier which resembles a standard fuel carrier. A special multi-pin coaxial connector is mounted on the front end of the fuelling machine ram which has been modified to allow fifteen coaxial wire to run down the middle. When the ram advances into the transducer carrier, it makes an underwater connection to the probes. At the back of the fuelling machine a specially designed cable rewinding mechanism reels and unreels a flat cable consisting of fifteen coaxial wires bonded together side by side and contains a high pressure cable seal which allows the signals to be sent through the fuelling machine pressure boundary. The required scanning motions are achieved by the normal fuelling machine drives while the data acquisition is handled by a computer console located in the reactor control room. Research Division accepted responsibility for the

ultrasonic probes and instrumentation, the data acquisition system and the cabling inside the fuelling machine, and the underwater connector.

Data Acquisition System

The data acquisition system has been designed around a Compaq 386 desktop computer. Two Krautkramer-Branson KB6000 ultrasonic instruments, the same typed used in CIGAR, simultaneously gather the data which is stored.

PIPE data acquisition and playback software was designed with several goals in mind. First and foremost, the software had to be user friendly and as intuitive as possible. To accomplish this, the user interface is based upon a system of menus and data entry panels. Messages are clearly displayed and used to keep the operator informed as to the state of the system. The interface between the DAS and the fuelling machine is automated to reduce the need for tedious operator interaction with the system. A number of important utility functions are also provided to aid the operator in setting up and verifying the correct operation of the hardware.

The PIPE DAS collects and processes huge volumes of raw data. To aid the operator in digesting this data, it is processed and presented as a set of full colour isometric displays which appear in real-time as the inspection is carried on. Hardcopy of these displays is produced on a multi-coloured dot matrix printer. Decisions on data and system integrity are performed automatically where possible but the operator is always able to override the computer when necessary.

Collected data is archived in its raw form. This allows complete flexibility in post inspection replay and analysis but requires that several megabytes worth of data e archived for each rolled joint inspected. To accommodate this volume of data, PIPE contains an optical disk storage system capable of storing 400 megabytes on a single replaceable disk cartridge.

The DAS software is somewhat user configurable. Parameters such as screen and printer colours are set by the user by editing a parameters file. Any changes made take effect immediately and no recompiling or relinking of the software is necessary.

Initial testing of the DAS was performed on a rolled joint mock-up at CGE in Peterborough. The testing went smoothly with only minor problems discovered. The system was then used to carry out a large scale inspection at Bruce NGS were the DAS system performed extremely well. System operators made several suggestions as to how the DAS could be improved and these suggestions will be implemented before the next use of the system.

Bruce PIPE – Commissioning

Components of the Bruce PIPE (Packaged Inspection Probe for Rolled Joint Evaluation) system were assembled at CGE in Peterborough for testing. Severe electrical noise on the ultrasonic test signals were encountered. The noise source was determined to be the fueling machine drive system. Shielding and filtering were devised to reduce the noise to acceptable levels. Various hardware and data

acquisition software problems were recognized and corrected and an endurance test equivalent to the inspection of 100 rolled joints was completed successfully.

Prior to the first use of the system on Bruce unit 2, tests of the cabling and the inspection systems were successfully carried out at the station to assure that the solution devised at CGE were applicable.

The first on reactor use of the system started September 21, 1987. After two days of commissioning, the system inspected 109 rolled joints in approximately six days.

PIPE Packaged Inspection Probe (Pickering Version)

Background

A rolled joint inspection system, which uses the fuelling machine as a delivery system, is being developed for use at Pickering. This system is similar to the one which has already been designed for Bruce NGS. A different system is required for Pickering due to fundamental differences between the Bruce and Pickering fuel handling systems.

BLIP – Blister and Spacer Location Inspection Probe

The discovery of high hydrogen content in the outlet end of Pickering Unit 3 pressure tube L-09 has raised concern about the fracture toughness of other pressure tubes. If the elevated hydrogen level is general, pressure tubes with misplaced garter spring spacers are at risk because of the possibility of pressure tube/calandria tube contact and the formation of blisters. Cracked blisters can act as initiators for delayed hydrogen cracking such as that which caused the failure of Pickering 2 pressure tube G16 in 1983.

A new inspection system, BLIP – Blister and spacer Location Inspection Probe, is being developed to rapidly survey the outlet ends of pressure tubes in Pickering type reactors. This joint program with Design and Development Division and Operations (CNS) utilizes the fuelling machine rams to move an inspection head carried in it's magazine through the outlet half of the pressure tube. The head has a CIGAR type eddy current spacer location coil and SLAR type ultrasonic blister detection transducers.

The OHRD-NDE Unit is responsible for the design and procurement of the inspection transducers, the inspection cabling inside the fuelling machine and the inspection control and data acquisition system. Although some of the components used are common to the PIPE system, the longer inspection stroke and different scan mode have required considerable changes. A new 14 conductor winch cable capable of withstanding retract loads up to 100 kg has been developed and life endurance tests are being performed. Major changes have been made to the PIPE control and data acquisition console to accommodate extra instruments. Also, new data acquisition software has been written for the new inspection. A testing simulating the operation of the Pickering fuelling machine has been built for PIPE testing and is being employed for BLIP commissioning tests.

Full Size Mechanical Simulation and Test Facility

A full size mechanical simulation and test facility has been set up at Research for simulating the actual operation of the Pickering fuelling machine in its PIPE inspection mode. This facility is required because unlike with the Bruce version, Pickering PIPE will not be tested on an actual fuelling machine prior to commissioning at site.

CIGAR

Overview

The entire CIGAR Data Acquisition System (DAS) was redesigned in 1987 with most of the hardware and all of the software being replaced with improved versions. The PDP 11/73 computer used to run the DAS was replaced by two Compaq 386 PCs and the software which was originally written in Fortran and PDP 11 assembly language is now written in C and Microsoft assembly language. With these changes, CIGAR acquired significant new features and capabilities. Some of these features have not yet been used in the field, but final integration and testing is expected to be complete by the end of March.

Gauging

The ultrasonic instrumentation to perform pressure tube gauging has been replaced with a Krautkramer WDMU ultrasonic thickness measuring device which is used to measure both pressure tube wall thickness and diameter. The data sampling rate has been increased to provide better resolution and all data is now stored digitally on floppy disk. Full data processing and graphics generation can be performed immediately after scan completion and requires only several minutes to complete.

Sag

The sag system changed very little during this upgrade. The major improvements are that data storage is now done on floppy disk and complete data processing and graphics generation takes less than three minutes.

Gap

The software to produce pressure tube – calandria tube gap estimates is not yet complete but this is due to the fact that the algorithm to compute this estimate is still under development. The software to collect the raw data has been implemented and tested.

Flaw Detection

The most drastically improved part of the CIGAR DAS is the flaw detection system. The Compaq 386 performing the flaw detection function is connected to a high resolution (1280 x 1024) colour graphics monitor, a colour ink-jet printer, and a 230 megabyte per cartridge optical disk storage system. Data is collected via a high speed analogue to digital converter at a rotary resolution of 0.1 degrees. Due to this high data collection rate, data files of approximately 80 megabytes in size are generated for each full pressure tube inspected.

CIGAR is now capable of producing up to four simultaneous, on-line, full colour isometric or C-scan plots of data being collected. The operator has complete control over which data will be displayed and has great control over display format items such as the colour spectrum used and the type of displays to be generated. Limited full colour hard copy is also produced on-line through the system colour ink-jet printer.

CIGAR Gap Measurement

The current design for the eddy current gap probe produces a signal that varies linearly with gap (pressure tube to calandria tube spacing). It also responds to variations in pressure tube wall thickness in a manner that is virtually indistinguishable from that due to gap. As a result, current systems utilizing this probe compensate the signal in a linear fashion using spot wall thickness measurements from an ultrasonic system.

This compensation scheme can lead to errors if the wall thickness varies significantly within the field of the eddy current probe. A project is underway to model the probe as a spatial filter and process a detailed map of the wall thickness in order to produce a more accurate compensation signal.

CIGAR Head Tester

The CIGAR head tester was completed and transferred to the field this year (Report M87-62-K). The unit plugs directly into the recessed 15 coax pin connector of the CIGAR head. It contains modules to test send-receive eddy current probes, ultrasonic transducers and the servo inclinometer used for sag measurements. The unit is bus oriented and is configurable for any head wiring configurations. It also contains a control unit capable of switching the proposed head multiplexer and connecting the appropriate test module to the signal lines. The unit is intended to quickly verify the basic operation and wiring of new and rebuilt heads before they are used with the complete CIGAR system.

CIGAR - Profilometry Inspection Head

A profilometry inspection head has been developed for the inspection of pressure tubes. This device consists of a profilometer, two standard CIGAR centering modules, ultrasonic and eddy current flaw detection modules, and a garter spring locating module. Of these modules, the profilometer was the only device that had to be newly developed. The performance objective of the profilometer was to produce profiles of pressure tube wear/erosion and to monitor debris damage in fuel channels. Six profilometers have been manufactured and successfully implemented for channel inspections on Pickering Unit 3 during June, 1987 and Gentilly No. 2 (Quebec) during August, 1987. Its satisfactory applications have shown that this device can provide the measurement capability and accuracy as required. It is, however, anticipated that an improved version of the profilometer will be developed to increase its operating accuracy and reliability.

CIGAR - Visual Inspection System

An effort has been made to incorporate a visual inspection device (TV camera) into the CIGAR system for fuel channel inspection. Studies have been conducted to in-

vestigate the possibility of using a Westinghouse miniature underwater TV camera for CIGAR applications. A laboratory test was done to examine the CIGAR cable effect on the TV camera picture quality and to study the lighting fixture cable requirements. The test results have shown that the miniature underwater TV camera and its controller can be modified to work under CIGAR conditions. The preliminary design of a special inspection head, which consists of a TV camera, has been completed.

CIRENE-CIGAR

Following the successful commissioning of the CANDU CIGAR (Channel Inspection and Gauging Apparatus for Reactors), the Italian Government approached New Business Ventures to buy a similar system for their CIRENE Reactor. The project was administered by Design and Development Division with Research Division providing technical assistance. This assistance involved redesign of inspection head components, software specification and liaison and help with equipment specification and assembly. The system was completed and shipped to Italy in May 1987 after extensive testing and software debugging in the laboratory.

Up and Coming

In 1988, it is hoped that CIGAR will acquire a combined analogue/digital interface to the KB 6000 ultrasonic set. This will allow the development of software to perform true B and depth encoded C-scans. The gap system may be finished by the end of this year and new systems are being developed and added as needs arise. It seems that CIGAR will never be "complete" as the system continuously grows and changes with Hydro's inspection requirements.

Darlington NGS Scanning Tool for Elongation Measurement (STEM)

A study of the feasibility of developing a non-contact STEM device was completed. The (airborne ultrasonics) STEM prototype was field-tested at Pickering Unit 7 in May 1986 and Pickering 8 in March 1987. The test results indicated that this device can provide the measurement capability and accuracy as required. Two STEM heads are currently being manufactured for Darlington NGS based on the ultrasonic concept. It is anticipated that two STEM systems will be ready for field test in June 1988. Work is now underway to develop other handtools for pressure tube elongation measurement.

1.3 Pressure Tubes

Pressure Tube Sag Measurement

Wet channel sag measurements are currently performed by CIGAR using a servo inclinometer. The lifetime of the unit is limited in reactor by the radiation tolerance of the on board electronics. As the replacement of the unit is costly both in parts and labour, an alternative is being sought.

A pendulum mechanism is being developed as a first option primarily because of limited axial space. A test rig has been constructed containing a pendulum mounted on a torsion bearing. The base inclination is murometer adjustable and is monitored by an existing inclinometer unit.

The motion of the pendulum is monitored by eddy current coil(s) which may be connected to instrumentation that CIGAR already possesses. The response of various coil arrangements will be compared to that of the servo inclinometer.

Darlington 4 Pressure Tube Manufacturing Inspection

Major modifications were made to the ultrasonic inspection of Darlington Unit 4 pressure tubes at Bristol Aerospace Ltd. A 100 MHz normal beam inspection was added to screen for lap-like manufacturing defects which resulted in the failure of the B2-N06 pressure tube. The conventional shearwave inspection was changed to incorporate CIGAR type spot focused probes, tube rotation and axial speed were reduced, and a much more sensitive and complete inspection was achieved. In addition, the gain level was increased to provide more low level ultrasonic information and thus a more useful archival record.

Pressure Tube Offcut Inspection

The high frequency UT inspection of pressure tube offcuts has been transferred to Babcock and Wilcox where all remaining offcuts of installed tubes are being inspected. In addition to screening for B2-N06 type flaws, the high frequency inspection has been capable of detecting high concentrations of zirconium carbide. This information is now being used in the selection of candidate tubes for CIGAR inspection.

Hydrogen Concentration Measurement

Recent work by K. Tashiro of the Materials Integrity Section has shown a correlation between pressure tube hydrogen concentration and characteristics of the resistivity vs. temperature curve between 20°C and 400°C.

A project is underway to develop a system to measure pressure tube resistivity change in the presence of local uniform heating. It will operate in a flooded fuel channel of a shut down reactor and be loaded by the fuelling machine in a fashion similar to BLIP.

A laboratory mockup of a fuel channel section has been completed. It contains seals to exclude water from the test area and a positioning mechanism to hold various probe assemblies. The first use of the mockup will be to evaluate methods of heating the pressure tube. Preliminary studies have been commissioned on the stress induced by local heating. Initial results are promising provided the heating is fairly uniform around the circumference.

Resistivity measurements are performed in the Materials Integrity laboratory by an AC potential drop method. Candidates for in-reactor use include this method as well as a non-contact eddy current technique currently under development.

Software to model bobbin style eddy current probes in the presence of layered coaxial conductors has been written in the ASYST language for use on a Compaq 386. The program is based on mathematics published in ORNL-5220 by Nestor, Dodd and Deeds. ASYST's support of complex number and array operations greatly enhances program readability. In many cases mathematical expressions are evaluated as written in the theoretical development.

The simulation software has been used to design a probe with optimized sensitivity, signal to noise ratio and linearity. The signal is taken to be the response to resistivity change as the pressure tube is heated and the noise as the response component due to expansion of the pressure tube.

The change in signal from an eddy current probe due to a change in its own temperature is potentially quite large. This problem is addressed by using a send receive design wound on thermally conductive ceramic former immersed in the reactor coolant flow and separated from the heat source by high efficiency insulation. The probe is currently under construction and will be evaluated for its baseline response in the laboratory fuel channel mockup.

Plans are being made to obtain a length of pressure tube with varying hydrogen concentrations for future evaluation of measurement systems.

Crack Depth Measurements in Pressure Tubes

Extensive progress has been made in measuring the depths of cracked blisters and fatigue cracks using crack tip diffraction. Experimental results show that depths can be measured within the range of +/- 0.1 millimetres on both types of defect. The optimum ultrasonic parameters are: 20 - 25 MHz frequency, 3 mm diameter probe elements, and incident/refracted angles of 50 - 55 degrees. One of the prime questions now is "What is the best position on the waveform to take measurements?" Three different signal processing techniques have been investigated to improve readability: auto- and cross-correlations, rectification and smoothing, and the magnitude of the analytic signal. None of the three techniques is optimum, and others (such as time-domain deconvolution) may be investigated. SAFT (Synthetic Aperture Focussing Technique) would probably be included to focus the B-scan images and improve signal-to-noise ratios. A CIGAR compatible sub-module is being investigated. An investigatory contract has been given to Prof. D.A. Hutchins of Queen's University to measure inside surface notches, specifically DHCs using the Delta or similar technique.

Hydride Platelet Concentration Measurements

Considerable emphasis has been put on this project, especially since P3 L09 was analyzed. Early in the year, Harwell/Oxford University imaged some hydride platelets at 370 MHz using defocussed scanning acoustic microscopy. By November, this result was duplicated by Sherbrooke University at 90 MHz. However, the images turned out to be of radially oriented hydrides, not circumferential hydrides. The images were formed by a complex wave interaction between longitudinal and surface waves, brought about by the slight difference in velocity between platelets and matrix. This acoustic microscopy technique could prove valuable for determining when near-surface radial hydrides were present, but will need to demonstrate its ability to penetrate the oxide layer. The real value of this result is to show that hydride platelets can be imaged using velocity difference approaches.

With this conclusion in mind, further contracts have been placed externally due to their specialized nature. Contracts have gone, or are going, to Harwell and Sherbrooke for further acoustic microscopy and microstructural investigations. Velocity measurements are being performed at high frequency at McMaster University, using bi-refringent shear waves at Queen's University, and using special EMAT-

generated wave modes at Magnasonics in New Mexico. As a back-up to the proposed eddy-current measurement of temperature-dependent resistivity changes, Magnasonics will also look at velocity changes as a function of temperature.

Pressure Tube Leak Detection Using Acoustic Emission

A pressure tube/endfitting mockup containing a controllable pin hole leak has been completed. The mockup will be used in the upcoming year to characterize acoustic emission from leaks in pressure tubes, as part of a COG supported program to improve acoustic emission techniques to detect pressure tube leaks in reactors.

Empirical PoD Model for Blisters

Further work on an empirical Probability of Detection (PoD) model has been performed. Ultrasonic scans on the TRAC II Zr-Nb blistered tube showed that predicted blister sizes are so small that, for ultrasonic purposes, they can be viewed as circumferential point reflectors. This has simplified the problem to a two probe, 2D model. Preliminary results using two axial transducers has shown that probabilities of detection at normal CIGAR scanning levels should approach 100% for blisters in the critical size range. However, if blister reflectivity is poorer than estimated, or scanning levels lower, PoD declines slightly. The model also indicates that PoD is not a simple function of raster size. Rather, the 3 mm step nominally used by CIGAR fortunately gives a high PoD. A 1mm step, as used for detailed scans, would give essentially a PoD of 100% for a blister of any significance.

Comparison of CIGAR and New Manufacturing Inspections

CRNL loaned COG pressure tube DB3 to both Bristol Aerospace in Winnipeg (BAL) and Research for comparing the new manufacturing inspection with a typical in-service inspection. Tube DB3 contains about 50 deliberately implanted defects of various sizes and orientations to evaluate pre-service inspection procedures. The CIGAR-type inspection performed at Research produced similar results to the BAL inspection. However, CIGAR scans are at higher gain levels, so four more defects were detected. Three defects were not detected by either inspection system. The signal amplitudes from the defects showed that CIGAR is at least twice as sensitive as the BAL inspections, which is not unexpected.

SLAR - Blister Detection System

The SLAR program has mostly been concerned with making the blister detection system functional in the SLAR tool, followed by determining what the system can see. Preliminary results from TRAC tube 11 showed that in general blisters of 0.3 mm were detected with some confidence, but that occasional blisters were completely missed. Further investigations of the blister's metallography will be performed to determine why the missed blisters were undetected. A successful SLAR ultrasonic head probe tester was built. Attempts to develop a simple single probe testing device were not satisfactory.

On-Power EMAT Transducer

An EMAT (ElectroMagnetic Acoustic Transducer) system is scheduled to be delivered in the Spring of 1988. EMAT devices stress the metal using magnets, then

generate an ultrasonic wave by pulsing with an eddy current coil. Thus EMAT devices in principle can be made radiation and temperature resistant.

Inspection of a Darlington 4 Pressure Tube

New manufacturing ultrasonic inspection procedures for pressure tubes have been implemented at Bristol Aerospace Ltd. The higher sensitivity recording has shown that many tubes exhibit areas with circumferentially oriented outside surface indications that are higher than usual surface noise but well within acceptance standards. These indications have been attributed to grinding marks although rudimentary visual and tactile examination of the surface could detect no difference between areas with and without indications. One Darlington 4 pressure tube was selected and shipped to the Research Division for further exploration. The ultrasonic indications were confirmed and visual microscopy and surface replicas of their locations have confirmed they they are due to local abnormal grinding marks approximately 0.03 mm deep x 4–5 mm long. Although not of concern to the structural integrity of the tube, it was important to confirm the source of the indications to aid in interpretation of in-service inspection results.

Inspection of Yttrium D_2 Sinks for Pressure Tubes

The deuterium level in the rolled joint region of pressure tubes is elevated due to ingress of D_2 from the endfitting. To reduce the buildup, it is planned to attach a D_2 getter made of Yttrium to each end of new tubes. (Darlington 4 tubes will be the first to have them). Yttrium is fairly reactive in water and hence must be completely encased in zirconium to protect it. An inspection method is required to measure the thickness of the zirconium cladding and to determine whether or not good contact exists between the zirconium and Yttrium. Samples of both extruded tube clad Yttrium and HIPed (hot isostatically pressed) D_2 sinks were inspected and methods for obtaining the required information were demonstrated.

1988 PROGRAMS

BLIP

The BLIP system will be completed in time for the Pickering Unit outage in early 1988.

A BLIP system for Bruce is being planned. Consultation on inspection, cabling and data acquisition systems will be provided.

B-Scan Interpretation of Pressure Tube Defects

The ultrasonic evaluation of pressure tube defects using B-scan and related techniques will be continued.

Crack Tip Diffraction for PT Crack Depth Measurement

Preliminary work on ultrasonic crack tip diffraction for measuring the depth of OD cracks in blisters will be checked and a module suitable for use on CIGAR will be designed and tested.

2.0 FRACTURE MECHANICS RESEARCH AND APPLICATION

2.1 Darlington Leak-Before-Break Program

Application of Elastic-Plastic Fracture Mechanics

One task in this project is to compute a fracture mechanics parameter, the J-integral, for postulated through-wall cracks in tee connections for both the reactor inlet and outlet headers, and hopefully to demonstrate their stability. Initially, shell models were used but, because of problems in the computer code used, these were abandoned in favour of fully three dimensional solid elements.

J-integral values obtained using the "virtual crack extension" technique were consistent with those obtained from the energy differences between analyses of models having slightly different crack lengths and subjected to internal pressure. However, discrepancies were found when concentrated forces or moments were applied. Many analyses, both elastic and elastic-plastic were performed changing model refinement, modelling details, etc. but although consistent results were eventually achieved for some cases, the reason for the discrepancy is still unclear.

Fatigue Crack Growth Modelling

Predictions are to be made of the fatigue crack growth of postulated part-through wall cracks in the primary heat transport piping as a part of the "defense-in-depth" strategy of the Darlington LBB program. This involved the development of a computer program to perform the calculations for an entire piping system.
To perform the crack growth predictions the stresses in the uncracked component are first calculated. From these stresses the crack-tip stress intensity factor is calculated by using well-known three-dimensional formulae taken from the literature for similar but simplified geometries. The fatigue crack growth is then integrated numerically by using methods given in ASME Section XI Appendix A.

The applied loads will be the actual loads calculated as a part of the ASME Section III class 1 piping stress analysis being performed by the Mechanical Design Department, Design and Development - Generation. These ASME Class 1 analyses are being performed by running the in-house piping stress analysis computer program STANPIPES. The volume of data describing the piping system and loads is large, and the fatigue crack growth computer program will interface directly with STANPIPES.

Darlington Leak-Before-Break Material Test Program J-Resistance Curves

The Darlington Leak Before Break (LBB) approach has been developed for large diameter (21, 22, 24 inch) SA106B heat transport (HT) piping and A105 fittings as a design alternative to pipewhip restraints and in recognition of the questionable benefits of providing such restraints. Ontario Hydro's LBB approach is based on the elastic plastic fracture mechanics (EPFM) method.

In order to assess the stability of HT piping in the presence of hypothetical flaws, the material value of the J-integral associated with crack extension, which is also known as a material resistance curve or a J-R curve, must be known. In this test program, J-R curves were determined from actual pipe heats that were used in the

construction of the Darlington heat transport systems (Units 1 and 2). Test blocks were prepared using four different welding procedures for nuclear Class I piping. Two SA105 vesselet forgings were also tested.

The test program was designed to take into account the effect of various factors such as test temperature, crack plane orientation, welding effects, etc, which have influence on fracture properties. The objective was to identify those factors which tend to lower the resistance curves and apply the appropriate lower bound resistance curves that were obtained from this program, for structural analyses. A total of 91 tests were conducted. An acceptable lower bound J-resistance curve for the piping steels was obtained by machining maximum thickness specimens from the pipes and by testing side grooved compact tension specimens.

Due to the size of the material test program, results were reported in two reports. The first report included a brief introduction to the elastic plastic fracture mechanics methods and the test procedure, summary of test results, discussion and major conclusions. The second report described the test method, calculations and interpretation of results, specimen configuration, dimension and preparation and documents all experimental test data for archival purposes. The entire data set was stored in a data base in the Mechanical Design Department's VAX computer for quick access and for application to the Darlington LBB project.

Test results showed that all product forms utilized in the construction of Darlington heat transport piping and all welds and heat affected zone materials within the scope of the Darlington Leak Before Break (DLBB) program exhibit uppershelf toughness behaviour. All specimens showed high crack initiation toughness, J_{Ic}, rising J-resistance curve and stable and ductile crack extension. Toughness of product forms depends on the direction of crack extension (circumferential versus axial crack orientation).

Toughness of DLBB welds and parent materials at 250°C was lower than that at 20°C. This behaviour is characteristic of low strength high toughness carbon manganese steels and welds and is possibly due to a drop in yield strength with temperature.

All welds within the scope of the the DLBB program were subject to suitable post weld heat treatment. Non post weld heat treated welds remained tough and ductile at 250°C, but showed comparatively lower J_{Ic} and J-resistance curves than those observed in post weld heat treated welds. However, toughness of non post-weld heat treated welds increased significantly after a post-weld heat treatment.

The test method for J-resistance curves was validated by comparing six test results against tests conducted by Material Engineering Associates (MEA) of Lanham, Maryland. The J_{Ic} and J-resistance curves obtained by Ontario Hydro and MEA were comparable. The comparison of Ontario Hydro and MEA tests and all MEA test results were presented in a report.

2.2 Pressure Tubes

Allowable Sizes of Blunt Flaws in Zr–Nb Pressure Tubes Under SLAR Loads

Cyclic stresses induced by the SLAR tool during the SLAR (Spacer Location and Repositioning) operation are much higher than the design stresses. The additional stress concentration to the root of blunt flaws may result in crack initiation due to mechanical fatigue. The allowable root radii precluding crack initiation for postulated flaws in pressure tubes subject to SLAR stresses was calculated for various depths. The consequences of performing the SLAR operation on pressure tubes containing blunt flaws could then be assessed.

The low–cycle fatigue calculations employed fatigue life curves which were generated from fatigue tests performed at AECL–CRNL on irradiated Zr–2.5% Nb material. Allowable blunt flaw sizes were also calculated for pressure tubes subjected to normal operating cyclic stresses only.

Fatigue Crack Growth of Zr–Nb Pressure Tube Material

A joint program with the Materials Integrity Section has been initiated to assess the fatigue crack growth behaviour of cold–worked Zr–2.5% Nb pressure tube material in a simulated CANDU PHTS environment. Fatigue crack growth rate data will be obtained at a temperature of 305°C and at an inlet channel temperature of 250°C. The effect of dissolved oxygen on fatigue crack growth, at concentrations representative of normal and boiling channel conditions, will also be established. Results of this program will greatly increase the confidence of future pressure tube flaw assessments and will also provide valuable information for design applications.

Emphasis to date has been on fabricating and commissioning the flow loop, which supplied hot pressurized water of controlled chemistry, to the test autoclave. An AT–compatible computer and fatigue software have been procured for controlling and monitoring the fatigue crack growth rate tests. Compact tension and four point bend specimens, having hydrogen concentrations of either 40 or 60 ppm, have been prepared. A high temperature clip gauge to measure crack growth, which is capable of operating in a high temperature water environment, has also been procured.

Preliminary commissioning of the test loop at elevated temperature has identified a problem with the pull rod seal which to date has prevented operation of the test loop at elevated temperatures. New packing materials, as well as a possible redesign of the seal, are being considered to minimize leakage of this seal.

Commissioning of a Pressure Tube Burst Test Facility

A new test facility that will permit fracture toughness tests to be performed on internally pressurized sections of pressure tube has been successfully commissioned. This facility is located in the tube test facility of the Materials Integrity Section and consists of a remotely located control room and a reinforced test chamber. Pressurization is performed by means of servo–hydraulic pressure intensifier, which is located outside the test chamber.

The intensifier is operated from the control room where the control console is interfaced with a computer. Cables running from the test chamber to the control room permit continuous monitoring of specimens pressure and temperature, and provision has been made to monitor crack extension via a direct current potential drop technique.

Test control software is currently under development for a research program to monitor the growth of surface cracks in pressure tubes. This facility will permit the effects of specimen geometry on fracture test results to be better understood and should aid in making more accurate predictions of critical defect sizes.

Zirconium Hydride Blister Cracking Tests

A large number of tests have now been performed in an effort to determine the conditions required to fully fracture a hydride blister, and thereby initiate a crack in a pressure tube. The earlier observed trend of a decrease in cracking stress with increasing blister size is still apparent although considerably more scatter has been added to the data.

It now appears that the relationship with size is an indirect one and the the more important parameters are related to the peak hydrogen concentration within a blister and to the internal hydrogen distribution. There is some indication that the relationship between size and cracking stress may not be linear. However, experimental scatter is sufficiently large that both linear and non-linear fits result in similar predictions of critical size for cracking under operating stress.

It appears that this critical size does not depend on whether the blister is grown under stress. It is also apparent that the cracking stress for a given size of blister is not significantly affected by either the blister growth temperature or the test temperature.

Currently, the data pertaining to over 130 test specimens is being analyzed in an effort to shed more light on the factors affecting blister cracking, and hopefully to develop a model of blister cracking with a sound theoretical basis as opposed to the empirical relationship currently available.

Effects of Hydride Morphology on Zr-2.5Nb Fracture Toughness

Work has continued to determine the effects of hydrogen concentration and hydride continuity coefficient (HCC) on the axial fracture toughness of Zr-2.5Nb pressure tube. Two series of tests were carried out in 1987 on small compact tension specimens prepared from tube sections that had been hydrided and cooled under an internal pressure of about 12 MPa. The first tube had a concentration of about 60 ppm and an HCC of about 0.1. The morphology consisted of a fairly uniform structure dispersed hydrides oriented between the radial and circumferential planes, referred to as mixed hydrides. The fracture toughness was found to be affected at temperatures below 175°C, by which temperature ductile behaviour was observed. The toughness values for this structure were essentially identical to those measured previously on a bonded structure of alternating radial and circumferential hydrides, having the same HCC value of 0.1. This suggests that HCC is a fairly useful quantity for use in predicting toughness.

The second structure tested had a concentration of about 40 ppm and an HCC of < 0.1 and was also a mixed morphology. This material exhibited high toughness at all temperatures.

In the future, tests will be performed on material having higher hydrogen concentrations and higher values of HCC. Once these tests are completed, a fairly complete database will have been generated on the effects of hydride and hydrogen concentration on unirradiated pressure tube toughness.

2.3 Plant Materials

Thermal Plant Flaw Evaluations

Analyses, using EPFM, of weld defects in the Lakeview and Nanticoke downcomers, and the Lakeview and Lambton distribution headers were performed at the request of CTS. In the former case, a parametric study was performed so that defects subsequently found can be assessed without further analysis.

Fracture Properties of Pickering 'A' Primary Head Weldment

A welded test plate had been fabricated to best simulate the primary head to tubesheet weldments in the Pickering 'A' steam generators. J-integral resistance fracture toughness curves were generated from laboratory tests performed on samples of the weld metal, base metal and heat-affected zone taken from the test plate. Tensile stress-strain curves were generated by the Materials Integrity Section, and Charpy impact energy data was generated by the Metallurgy Section, to complete the data required to perform an elastic-plastic flaw evaluation.

Fracture Toughness of A-516 Gr 70 Pressure Vessel Steel

An extensive material test program to characterize the fracture toughness behaviour of A-516 Gr 70 steel base metal and weldment has been completed. This steel is commonly used in both CANDU stations and heavy water plants. The program was initiated because little information was available on its toughness characteristics at normal plant operating temperatures. The intent of the program was to obtain lower bound material fracture properties, as determined by using an elastic-plastic J-resistance curve approach.

Specimens were prepared from five different plates of this steel, which ranged in thickness from 51 to 127 mm. Compact tension specimens were machined at various orientations from the central region of the plate, since this region was likely to contain the highest density of segregated impurities, and therefore the worst fracture properties. Weldments were fabricated from three 127 mm thick plates using a submerged arc welding procedure typical of that used for welding the primary head to the tubesheet of a steam generator. This procedure has a relatively high heat input which should give a relatively coarse microstructure having lower bound fracture properties. Specimens were prepared from the weld metal and along the weld heat affected zone.

Fracture toughness J-tests and tensile tests carried out in the temperature range 20-300°C revealed a minimum in the fracture toughness at 250°C. The fracture toughness of the base metal plates was largely dependent on the inclusion content

of the steel. The higher sulphur content steels tested in this program (0.019% S), having a greater volume fraction of nonmetallic sulphide inclusions, generally had lower fracture toughness. In general, the fracture toughness of the heat affected zone was comparable to that of the parent metal, and the fracture toughness of the weld metal was slightly lower than that of the parent metal.

Fracture Properties of Downcomer Weld of Lakeview TGS, Unit 5

Life assessment work being carried out at Lakeview TGS disclosed cracking in circumferential and longitudinal seam welds in some downcomers of Unit 5. A metallurgical examination revealed that the cracks were approximately 10–15% of the through–wall thickness and were typical of corrosion–fatigue type damage.

The fracture properties of this material were determined in order that a fracture mechanics analysis could assess the structural integrity of these damaged components. Fracture toughness J–tests and Charpy v–Notch impact tests were carried out to characterize the material fracture properties. Charpy tests showed that the indexing temperature, RT_{NDT}, was approximately –13°C. Fracture toughness J–tests at 20°C showed predominantly ductile crack growth. Unstable crack growth, after a limited amount of crack growth, was exhibited during one test, but this behaviour was expected because the test temperature of 20°C was in the upper temperature range of the ductile–brittle transition region. The fracture toughness at the initiation of crack growth, J_{Ic}, was determined at 60 and 365°C and indicated that the weld metal had reasonable fracture toughness.

Fracture Toughness of PN–229 Submerged Arc Weld Metal

The fracture toughness tests performed for the Darlington leak–before–break assessment revealed that some non–stress relieved submerged arc weld material displayed significantly lower initiation toughness (J_{Ic}) values at 250°C. The lower toughness was also reflected in the post–initiation resistance curve and was of particular concern for specimens prepared using weld procedure PN–229 which demonstrated brittle crack "pop–in" after some ductile tearing when tested at room temperature. To further quantify these observations crack growth resistance curves were obtained for PN–229 weld metal specimens in the non–stress relieved and stress relieved conditions. The serrated flow or dynamic strain aging behaviour of this weld was also evaluated, as it was believed that this mechanism may be responsible for the observed toughness reduction.

The fracture toughness of the as–welded and stress relieved weld specimens was characterized at 20 and 200°C. This upper test temperature was identified from a comprehensive tensile test program as having pronounced serrated flow typical of that associated with dynamic strain aging.

The fracture toughness tests carried out at 20° indicated that both the as–welded and stress–relieved welds had high J_{Ic} values ranging from 240 to 350 kN/m, with the as–welded specimens having slightly lower fracture toughness values. The tests performed at 200°C showed a dramatic increase in fracture toughness on stress relief. The as–welded specimens exhibited J_{Ic} values which were nearly identical to those observed in the Darlington LBB program and ranged from 66 to 141 kN/m. The stress relieved specimens displayed a three fold increase in initiation fracture toughness with values ranging from 309 to 398 kN/m.

These results are consistent with the reported manifestations of dynamic strain aging. The load–displacement curves of the as–welded specimens showed marked load fluctuations during stable crack extension, whereas the stress relieved specimens did not. It is believed that the as–welded specimens were susceptible to dynamic strain aging. In this case, dissolved carbon and nitrogen atoms, which are known to be present in relatively high concentrations in as–welded weld metal, impede dislocation motion and reduce the amount of plastic deformation occurring during fracture. Stress relieving immobilizes the carbon and nitrogen solute atoms by forming stable carbides and nitrides, and thus restores material toughness. A chemical analysis of the as–welded and stress relieved specimens is being carried out to confirm this explanation.

2.4 Analytical Fracture Mechanics

Finite Element Mesh Generator

A major task in a three–dimensional finite element analysis is the generation of the finite element mesh. Typical three–dimensional (3D) models used in the Darlington leak before break program can easily extend to 50 pages of input data. A proprietary mesh generation program was available but was found to be very slow (a single mesh might take 3 days to generate) and would not permit certain necessary mesh details such as collapsing crack tip elements.

A specialized interactive mesh generator computer program was developed to perform the specialized functions required to generate finite element models of components containing flaws. A rudimentary shell mesh representing only the basic geometry of the model is first generated using the solid modelling features of the proprietary code. This mesh is then transformed into a detailed 3D mesh using the in–house code.

Generic Calculations of Part–Through Flaws

The elastic–plastic J–integral was calculated for a limited category of three–dimensional part–through circumferential flaws in a pressurized cylinder.

2.5 External Activities

i) ASME Section XI Flaw Evaluation Working Group Activities

The FM Unit is continuing to keep abreast with developments in flaw evaluation procedures for Section XI of the ASME Boiler and Pressure Vessel Code. A member of the Unit is participating in Section XI meetings and development of Code procedures.

ii) Presentation of EPFM to the CSA

A seminar on the application of elastic–plastic fracture mechanics to flaw evaluations was made to the CSA N285B Technical Committee on Inservice Inspection and Flaw Evaluation.

iii) Research Project to Develop Shallow Crack Fracture Mechanics Tests

Ontario Hydro is a sponsor of an international research project to develop shallow crack fracture mechanics tests. This project is being carried out at The Welding Institute (Cambridge, UK) and the Edison Welding Institute (Columbus, Ohio). The Fracture Mechanics Unit is Ontario Hydro's representative for this project, while the sponsor's fee is provided by the Chemistry and Metallurgy Department of CNS.

1988 WORK PROGRAM OUTLINE - FRACTURE MECHANICS

Darlington Leak-Before-Break Program

The calculation of the J-integral for the tee connections at the reactor inlet and outlet headers will be completed and documented. The validation and documentation of the fatigue crack growth computer program will be completed.

Pressure Tubes

The elastic-plastic J-integral will be calculated for laboratory compact-tension specimens fabricated from Zr-Nb pressure tubes. The elastic-plastic J-integral for through-wall cracks in pressure tubes will also be calculated. A study of the ranges of validity of the elastic-plastic J-integral with regard to geometry and loading conditions will be performed for both the compact-tension specimens and the through-wall cracks in pressure tubes.

Development of J-Integral Evaluation Software

In-house software will be developed to calculate the J-integral under three-dimensional elastic-plastic conditions. The algorithm will be based on the Virtual Crack Extension Method.

Finite Element Mesh Generator

Further modifications will be made to the in-house finite element mesh generator computer program to allow models to be generated from "scratch" for components containing a wider range of flaw types.

Analytical Fracture Mechanics

The implementation of three-dimensional part-through flaw models into the FM Unit's in-house EPFM flaw evaluation computer program will be completed.

Fatigue Crack Growth of Zr-Nb Pressure Tube Material

The objective of this program, which will be jointly carried out at Ontario Hydro and CRNL, is to assess the fatigue crack growth rate behaviour of Zr-2.5Nb pressure tube material in a simulated CANDU PHTS environment. Work at Ontario Hydro will concentrate on evaluating environmental effects, such as high dissolved oxygen concentrations, while work at CRNL will address effects of irradiation on the fatigue crack growth rate.

The test program will examine a large number of test variables that may affect the fatigue crack growth rate. For this reason, an additional refreshed autoclave will be purchased early in the year.

Once specimens have been prepared initial tests at both sites will use similar test variables to show consistency between sites. Following these tests work at Ontario Hydro will evaluate the effect of high dissolved oxygen concentrations, representative of boiling channel conditions, on fatigue crack growth rates of as-received pressure tubing.

Fracture Toughness of Heavy Water Plant Blistered Steel

Many vessels currently in service at BHWP possess varying amounts of damage from internal hydrogen blistering which may be degrading the pressure containment. A fracture toughness test program will be carried out on blistered steel received from BHWP to aid in establishing safe operating limits and retirement criteria for these damaged vessels.

Workshops and Conferences

A three day workshop on Fracture Mechanics and Nondestructive Evaluation was held at Ontario Hydro Research. Presentations were made by invited lecturers on the following topics:

Fracture Mechanics Testing	B. Mukherjee, Ontario Hydro Research
Computer Aided Testing	U. Mohaupt, U. of Waterloo
Nondestructive Evaluation	J.A. Baron, Ontario Hydro Research
Flaw Evaluation	D.J. Burns, U. of Waterloo
Computational Fracture Mechanics	R.J. Pick and R. Hoff, U. of Waterloo
Failure Analysis	J.I. Dickson, Ecole Polytechnique

The workshop was attended by twenty-seven participants.

An International Symposium on fracture was chaired jointly by W.R. Tyson of PMRL/CANMET and B. Mukherjee of OHRD. The symposium was sponsored by the Metallurgical Society of CIM and the Canadian Committee for Research on the Strength and Fracture of Materials. The following topics were addressed at the Symposium:

Testing and Mechanics - Metals	(6 papers)
Testing and Mechanics - Non Metals	(6 papers)
Fatigue and Fracture of Weldments	(6 papers)
Materials Development and Microstructural Property Relationship	(6 papers)
Fracture Mechanics Tutorial - State of the Art	(6 invited papers).

The proceedings of the Symposium is being published by Pergamon Press.

III- SUPPORT TO THE EXTERNAL COMMUNITY

Our facilities and expertise in both fracture mechanics and nondestructive evaluation are amongst the highest rated in Canada. To maintain this position it is es-

sential that we enjoy a continual influx of new ideas which we can then direct to the advantage of the Corporation. It is also incumbent upon us to ensure that we also support the technological community in which we operate and in which we thrive. This is done by presentations made at conferences, externally published work and also more direct support to local professional bodies and institutions of learning. A few examples of this involvement are listed below.

University of Toronto

Mr. K.-E. Lindenschmidt was granted a Master of Applied Science degree for his work conducted in the Section's laboratory. Mr. Lindenschmidt's project involved the application of ultrasonic crack tip diffraction to blister crack sizing in pressure tubes.

Dr. B. Mukherjee, Unit Head – Fracture Mechanics, was appointed as adjunct professor in the Mechanical Engineering Department.

Canadian Committee for Research on the Strength and Fracture of Materials (CSFM)

The Fracture Mechanics Unit organized and conducted a 3 day CSFM Workshop/Course on Fracture Mechanics and Non Destructive Evaluation in March 1987. Speakers were from both within and external to Hydro. The workshop featured a "hands-on" approach.

NDE Institute of Canada

Members of the Section continue to support the NDE Institute through donations of personal time to teaching NDE subjects, in providing advice on relevant matters, and in acting as trustee to the Institute.

A donation of some surplus automated ultrasonic equipment was made to the Institute.

Canadian General Standards Board

A member of the Section is currently the Chairperson of the Committee on the Certification of NDT Personnel and also represents the interests of the Corporation on the Coordinating Committee. In this capacity, the Chairperson is interfacing with the NDT community as a whole and the Federal Ministry controlling the operation's of CANMET in addressing the initiative to privatize the NDT Certification program.

United Nations

At the request of the United Nations Industrial Development Organization, John Baron spent five weeks teaching topics in nondestructive evaluation in the People's Republic of China.

IV – THE VALUE OF FORWARD LOOKING RESEARCH

In recent years, and especially 1987, the Section has been highly successful in applying its research endeavours in a real and practical sense for the benefit of the Corporation. There can be no question as to the value to the Corporation of projects such as the Darlington Leak Before Break project or the contribution to PIPE, etc. However, all of these problem solving endeavours rely on expertise, experience and knowledge gained from research, or at least, less applied projects, as well as previous problem solving exercises.

The Section has been highly successful, which in turn gives our clients the confidence to come back for new applications or modifications to old ones. Further, there is no doubt that problem solving is very rewarding on a personnel level because it gives the individual a sense that he or she is needed, the contribution is valued and there is clear manifestation of the success of one's toil. Success builds on success, and it is only too easy t o lose sight of the fact that we have only been successful problem solvers because we had built up a solid base of knowledge in forward looking endeavours over the years. Moreover, our clients acknowledge our abilities, facilities and credibility and are eager to make use of our talents, even when the request may not be in keeping with our Corporate role.

If we are going to maintain our significant contribution to the Corporation, we must prepare for the future now! In an R&D setting that means being innovative, creative and willing to take technological risks. To attempt something that doesn't work out isn't failure but not to take such a risk is abdication of our role as researchers.

The work of the Section may be seen as a spectrum. At one end there is the direct application of knowledge to a well defined problem. At the other extreme are the fundamental investigations, the testing of ideas, and in the middle is the transition from ideas towards applications. We have done exceptionally well at the one extreme, but at the expense of the "ideas" end and the mid section.

In this regard, the work funded by the Candu Owners Group is of very high quality and value. The solid support provided by COG allows us to "fill in" the middle, without imposing the feeling of guilt because the end product may not be a shiny piece of machinery. Further, the management of COG recognizes the risk in research work and realizes that sometimes things just don't work out the way we hoped.

Now having won the continued success at the applications end of the spectrum and having COG support forward looking applied research, we are free to use our OM&A funds to try new ideas. Risk is a four letter word and we must make it part of our culture.

V – SUMMARY

The NDE Unit maintained its intensive involvement with fuel channel inspection and delivery systems. In terms of the latter endeavours, significant effort was expanded in up-dating CIGAR including the data acquisition systems, completion of the inspection head tested, a profilometry head and a visual inspection capability. Early in the year, the CIRENE-CIGAR system was delivered to Italy. PIPE was

another inspection system that was brought to fruition during the year, achieving the inspection of 109 rolled joints at Bruce Unit 2. Even before the completion of PIPE work was underway on a modification, BLIP, that would allow garter spring and blister detection at Pickering.

Outside of the inspection/delivery system development, significant advances were achieved in more fundamental aspects of NDE. In acoustic emission technology, success is reported in detecting flaw growth in fibre reinforced rubber. Several important achievements are reported in ultrasonic technology including the use of crack tip diffraction for defect depth estimation in pressure tubes, the use of a water jet in conjunction with a robotic manipulator to inspect closure welds on candidate spent fuel canisters, high frequency ultrasonic inspection of pressure tubes and the application of synthetic aperture focussing for thick material testing. Advances in eddy current technology are related to pressure tube/calandria tube spacing measurement, crevice corrosion pit dimension estimation, and steam generator tube/tubesheet separation. In terms of spatial measurement technology achievements in development of fuel channel elongation measurement systems and fuel channel sag are reported.

The Darlington Leak Before Break project remained the largest single endeavour in the Fracture Mechanics Unit related to the application of elastic-plastic fracture mechanics. This project included computation of the J-integral by various analytical and experimental techniques, fatigue crack growth modelling, and materials testing to generate J-resistance curves. The Fracture Mechanics Unit was awarded the Research Division's Director's Award for the work on the leak-before-break case.

Much of the Unit's experimental work was directed at pressure tubes, including: investigation of the effect of the SLAR tool operation in terms of production of high cyclic stresses, the growth by fatigue of cracks in pressure tube material, investigation of conditions under which hydride blisters crack, and the investigation of the effects of hydride morphology on fracture toughness. In addition, a new experimental system that will perform burst tests on pressure tube samples has been commissioned.

The application of elastic-plastic fracture mechanics is growing, including the investigation of weld defects in Lakeview and Nanticoke downcomers, the generation of J-resistance curves for the primary head to tubesheet weldments in Pickering steam generators and characterization of fracture toughness behaviour of A516 Gr 70 pressure vessel steel. The work related to Darlington Leak-Before-Break revealed a particular welding procedure produced lower initiation toughness values. This discovery was verified and investigated further.

A notable accomplishment in analytical fracture mechanics was the development of a specialized interactive finite element mesh generator program.

Both the NDE and Fracture Mechanics Units have undertaken work programs funded by the Candu Owners Group (COG) under the Fuel Channels Program. In all, four projects have been directly supported by COG.

Approved:

James Brown

J. Brown
Manager
Metallurgical Research Dept

Prepared:

J.A. Baron

J.A. Baron
Section Head
Nondestructive and Fracture Evaluation Section

/SEHG